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RATES OF OBSERVABLE BLACK HOLE EMERGENCE IN SUPERNOVAE

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ABSTRACT

A newly formed black hole may be directly identified if late-time accretion of material from the base of the ejected envelope generates a luminosity that is observable in the tail of the supernova light curve. In this work we estimate the rate at which events where the black hole "emerges" in the supernova light curve can be detected with present capabilities. Our investigation is based on an analytical model of the accretion luminosity at emergence as a function of progenitor mass, coupled to the inferred rate of observed Type II supernovae in nearby galaxies. We find through a parameter survey that under optimistic assumptions the potential rate of observable events can be as high as several per year. However, supernovae which produce black holes are also likely to be low energy explosions and therefore subluminous, as was the case for the best candidate to date, SN1997D. If black hole-forming supernovae are underdetected owing to lower luminosities, the rate of observing black hole emergence is probably not larger than once every few years. We therefore emphasize the importance of dedicated searches for nearby supernovae as well as faint supernovae projects for improving the prospects of observationally certifying the supernova–black hole connection.

Subject headings: accretion, accretion disks — black holes — supernovae: general

1. INTRODUCTION

Theoretical studies of core-collapse supernovae suggest that the remnant they leave behind can be either a neutron star or a black hole. The nature of the remnant is determined mostly by the amount of material the collapsed core accretes while the explosion is still progressing: if the final mass of the core exceeds the maximum mass it can sustain, it will collapse to a black hole rather than evolve to a stable neutron star.

Observational support for this theoretical scenario is not complete. Radio pulsar emission and x-ray observations provide observational evidence associating neutron stars with sites of known supernovae, but similar evidence for a black hole - supernova connection is still mostly unavailable. Indirect evidence that the black hole candidate in the x-ray binary system GRO J1655-40 was formed in a supernova explosion has recently been reported by Israelian et al. (1999). They base their inference on the relatively high abundances of nitrogen and oxygen on the surface of the companion, which has too low a mass to have produced such abundances by thermonuclear burning. Assuming those elements were deposited on the companion by the supernova explosion of the primary star provides indirect evidence of a black hole formed in a supernova.

In a series of recent papers we examined the prospects of directly identifying a black hole created in a supernova through late-time accretion onto it (Zampieri et al. 1998a,b; Balberg et al. 2000). Such accretion is powered by material from the base of the ejected envelope which remains bound to the black hole and gradually falls back and is accreted. Analytic (Colpi et al. 1996) and numerical (Zampieri et al. 1998a) investigations showed that the rate of late-time spherical accretion, when it becomes dust like, is expected to decline as a power law in time and so is the corresponding accretion luminosity. Such an accretion luminosity will produce a distinct signature on the total light curve if and when it becomes comparable to the output of other power sources, i.e., the initial internal energy of the envelope and decays of radioactive isotopes synthesized in the explosion. If detected, the unique time dependence of the accretion luminosity due to fall back would be a direct sign of the black hole "emerging" in the supernova light curve.

To date, black hole emergence in supernovae is yet to be observed. The prominant obstacle is that radioactive heating in the light curves of typical core collapse supernovae obscures any accretion luminosity for very long times. Even though radioactive heating decays exponentially while accretion luminosity declines only as a power law, the absolute power in radioactive heating remains the dominant source of the light curve until the supernova is no longer detectable. The case of SN1987A is a useful example (Zampieri et al. 1998a): while no firm evidence of a newly formed neutron star has been found, positive indication of the presence of a black hole (if one was produced) would be unobservable due to radioactive heating for about 1000 years.

Viable candidates for observing black hole emergence are supernovae which show very little radioactive heating. In principle, larger mass remnants, which are more likely to be black holes (Fryer 1999), are also more likely to be associated with supernovae which show diminished abundances of radioactive isotopes. Radioactive isotopes are produced in the deepest part of the exploding star, and therefore can be absorbed in a larger remnant in the earliest stages of fallback (Woosley & Weaver 1995). The best two recent candidates for supernovae which ejected very little radioactive isotopes and possibly produced black holes were SN1994W and SN1997D. In SN1997D the abundance of ^{56}Co inferred in the light curve was only $2\times10^{-3}\ M_\odot$, and the explosion energy was estimated as only 4×10^{50} ergs, both significantly lower than typical in Type II supernovae (Turatto et al. 1998). Our previous analyses (Zampieri

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et al. 1998b; Balberg et al. 2000) focused on SN1997D and showed that a $3\ M_\odot$ black hole in its remnant may emerge about 1000-1200 days after the explosion. Unfortunately, even at emergence the luminosity would have been only marginally detectable with HST. In the case of SN1994W $2\times10^{-3}\ M_\odot$ of ^{56}Co was the upper limit for radioactive heating, so the accretion luminosity might have emerged much earlier (and at higher value than in SN1997D). Unfortunately (again) the tail of the light curve was apparently dominated by circumstellar interaction (which was absent in SN1997D), and thus obscured any weaker source of heating from inside the envelope (Sollerman et al. 1998).

Can we expect better success in a systematic quest for observing black hole emergence in supernovae? Our goal here is to perform a first estimate of the potential rate of observations, and examine possible strategies for improving the prospects of such an observational search. We base our estimate on an analytic approximation for the luminosity at emergence of a black hole in a supernova as a function of progenitor mass, and then couple it to estimates of the rate of supernovae in nearby galaxies. Although the model is crude and excludes several details which determine specifics of supernovae explosions, their light curves and remnant formation, we are able to point to some underlying features. Our conclusions suggest that the likely rate at which black hole emergence can be observed with present capabilities and supernovae searches is probably once every several years, although with favorable assumptions this rate can be as high as about once a year. We also find that the dominant factor in determining this rate is most likely the difficulty of detecting nearby faint supernovae. A systematic search for such supernovae would significantly enhance the probability of discovering black hole emergence and observationally confirming the black hole - supernova connection.

We begin in § 2 where we develop the model that relates the emergence luminosity to progenitor mass. This function serves as the basis for estimating the values of emergence luminosities, presented in § 3. The main results are given in § 4, where the emergence luminosities are coupled to a distribution of progenitor masses, allowing for estimates of the rate of observable supernovae in nearby galaxies and providing us with an estimate of the rate of observable black hole emergence events. Conclusions and discussion are given in § 5.

2. THE MODEL

To assess the observability of black hole emergence we must first determine the accretion luminosity of the black hole and its value at emergence. We employ a simplified model in which the emergence luminosity, L_{BH}, is a unique function of progenitor mass, M_*. This is clearly a crude approximation, since explosion energy, black hole mass and post-shock evolution are likely to be dependent on other factors, such as progenitor rotation (Fryer & Heger 2000), metallicity (Woosley & Weaver 1995) and effects of a binary companion (Willstein & Langer 1999). Nonetheless, such an approach is a useful first approximation for deriving the observable event rate (and indeed is frequently used in other applications regarding core collapse supernovae, such as determining the neutron star and black hole initial mass functions; see Timmes, Woosley & Weaver 1996, Fryer 1999, Fryer & Kalogera 1999). We discuss some of the limitations and uncertainties concerning the unique function $L_{BH}(M_*)$ towards the end of this section.

2.1. *The Accretion Luminosity*

Constructing the function $L_{BH}(M_*)$ requires the time-dependence of the luminosity due to accretion onto the black hole. As shown analytically by Colpi et al. (1996) and numerically by Zampieri et al. (1998a), at late times after the explosion, *spherical* accretion onto the black hole becomes dust-like, and the accretion rate, $\dot{M}$, declines as $\dot{M}\propto t^{-5/3}$. Zampieri et al. (1998a) also showed that the resulting accretion luminosity is consistent with the Blondin (1986) estimate of hypercritical accretion, where $L_{acc}\propto\dot{M}^{5/6}$, so that

$$L_{acc}\propto t^{-25/18}\ . \tag{1}$$

This is a fundamental prediction of spherical accretion onto a black hole following a supernova, and can serve as distinct signature of accretion in the overall light curve (Zampieri et al. 1998a; Balberg et al. 2000). We address the question of likelihood of spherical accretion later in this section.

The proportionality constant in equation (1) is dependent on the black hole mass, M_{BH}, and on the properties of the bound material, including composition, density and velocity profiles. For the purpose of an analytic estimate an effective time, t_{dust}, can be defined so that

$$L_{acc}(t)=L_{Edd}\left(\frac{t}{t_{dust}}\right)^{-25/18} \tag{2}$$

where $L_{Edd}=4\pi cGM_{BH}/\kappa$ is the Eddington luminosity for material with opacity κ accreting on a black hole of mass M_{BH}. For bound material which initially has a uniform density, ρ_0, and a homologous velocity profile, $v(r,t=0)=r/t_0$ (where t_0 is the *expansion time scale*), the time t_{dust} can be roughly estimated as (Balberg et al. 2000, eq. [30])

$$t_{dust}=5.675\left(\frac{\mu}{0.5}\right)^{-4/5}\left(\frac{\kappa}{0.4}\right)^{3/10}\left(\frac{M_{BH}}{M_\odot}\right)^{-1/5} \left(\frac{\rho_0 t_0^3}{10^9\ \mathrm{gm\ cm^{-3}\ s^3}}\right)^{1/2}\ \mathrm{days}\ , \tag{3}$$

where μ is the mean molecular weight of the bound material. This estimate for t_{dust} includes the effect of radiation pressure during the earliest phase of fallback, when an accretion luminosity at about the Eddington limit modifies the flow of the bound material. This seems to be the case for realistic supernova envelopes (see Balberg et al. 2000 for details). We emphasize that the time t_{dust} is an effective quantity: at that actual time after the explosion the accretion is not expected to have settled into dust-like motion. Rather, t_{dust} corresponds to the time when the luminosity *extrapolated back from late-time* equals the Eddington limit.

2.1.1. *Explosion Energy and Black Hole Mass*

Equation (3) introduces the quantities required for estimating the accretion luminosity. For a given progenitor, these quantities are determined primarily by the explosion energy and the manner in which it is distributed in the envelope. We follow the approach of Fryer & Kalogera (1999), and parameterize the explosion by the total energy available for the through core collapse, E_{exp}, and the fraction, f, of this energy which is spent on unbinding the star. The remainder of the explosion energy is converted mostly to kinetic energy of the ejected material.

The energy available to unbind the star can be combined with the binding energy profile of the progenitor to calculate the remnant mass, M_{rem}, as a function of M_* according to

$$f\times E_{exp}=\int_{M_{rem}}^{M_*}E_{BE}(m)dm\ , \tag{4}$$

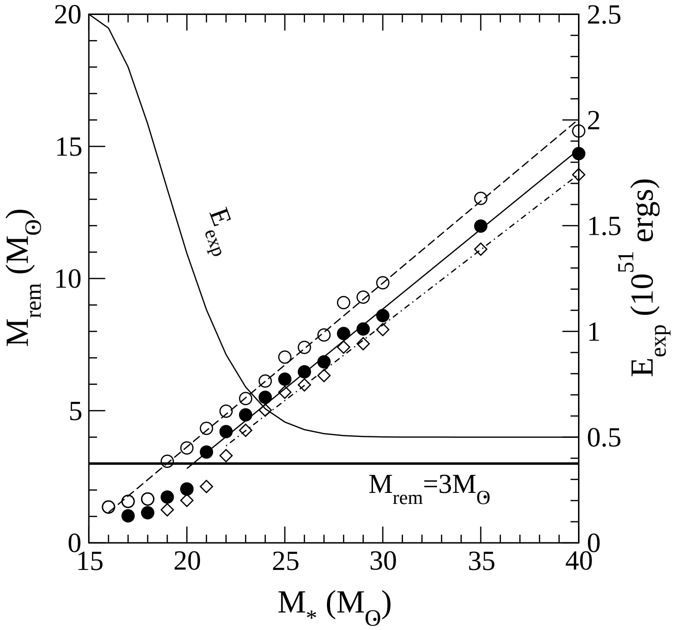

FIG. 1.— Estimate of the total explosion energy, E_{exp} (eq. [5]) and predicted remnant mass, M_{rem} as a function of progenitor mass, M_*, for different values of the parameter f (top to bottom: $f = 0.25, 0.50$ and 0.75). Data points correspond to the values from the numerical model (eq. [4), lines are linear best fits for the $M_{rem}(M_*)$ function for high mass remnants. The solid line at $M_{rem} = 3\ M_\odot$ marks the assumed threshold mass for black hole formation.

where $E_{BE}(m)$ is the binding energy profile, for which we use the massive star models of Woosley & Weaver (1995). Figure 1 shows the remnant mass versus progenitor mass relation found with $f = 0.25$, 0.5 and 0.75 where we adopted an analytic explosion energy function of

$$E_{exp} = 10^{51} \times \left[0.5 + 2\exp\left(-\frac{(15 - M_*)^2}{30}\right)\right] \ \text{ergs}\ , \quad (5)$$

for M_* in units of $M_\odot$. This energy function (also plotted in Fig. 1) is based on a fit to 2D core-collapse simulations of progenitors in the range $8 \leq M_* \leq 40\ M_\odot$, evaluated as the change in energy before collapse and after about 1 second of the material that experiences explosive shock heating. (Fryer 1999). Note that for the higher range of progenitor masses, which are the candidates for forming black holes, the remnant mass varies about linearly with the progenitor mass. Obviously, the remnant mass increases with decreasing f.

The nature of the remnant depends on whether its mass exceeds the maximum mass of a neutron star. As a conservative lower limit we will require $M_{rem} \geq 3\ M_\odot$ (baryonic mass, which is that found in eq. [4]) for the remnant to be a black hole. This consistent is with most realistic equations of state (see Cook, Shapiro & Teukolsky 1994).

2.1.2. *Properties of the Bound Material*

The estimate of the accretion luminosity includes a dependence on both the composition and kinetic energy of the bound material. For a homologously expanding medium the combination $\rho_0 t_0^3$ can be expressed in terms of the global quantities of the post-shock helium-rich layer, which is the source of the late-time accretion (Balberg et al. 2000):

$$\begin{aligned}\rho_0(\mathrm{He})t_0^3 &= 0.222 \times 10^9 \left(\frac{M_{\mathrm{He}}}{M_\odot}\right)^{5/2} \quad (6)\\ &\left(\frac{E_{kin}(\mathrm{He})}{10^{49}\mathrm{erg}}\right)^{-3/2}\ \mathrm{gm\ cm^{-3}\ s^{-3}}\ ,\end{aligned}$$

where M_{He} is the mass of the layer and $E_{kin}(\mathrm{He})$ is its total kinetic energy.

The mass of the helium layer can be estimated by subtracting the remnant mass calculated in equation (4) from the mass of the helium core of the progenitor. We parameterize the kinetic energy of the helium layer as a fraction, f_{He}, of the total kinetic energy delivered to the ejected envelope: $E_{kin}(\mathrm{He}) = f_{\mathrm{He}}(1 - f)E_{exp}$. Simulations of Type II explosions typically suggest that f_{He} is of the order of a few percent (Nomoto et al. 1994; Arnett 1996), generally decreasing for larger mass progenitors. The exact value does, however, depend on the details of the explosion and on progenitor structure.

2.2. *Emergence Time and Luminosity*

The black hole mass and the effective time t_{dust} uniquely determine the time dependent accretion luminosity (eq. [2]) which can then be compared to other sources of emission in the supernova. Specifically, we define the time of emergence, t_{BH}, as that when the accretion luminosity reaches $\frac{1}{2}$ of the total bolometric luminosity. This time and the corresponding emergence luminosity, $L_{BH} \equiv L_{acc}(t_{BH})$, depend on the source of luminosity with which accretion competes. This source is either the initial internal energy deposited in the envelope by the explosion, or ongoing heating due to decay of radioactive isotopes.

The radioactive isotopes relevant to powering the light curve, $^{56}\mathrm{Ni}$ and its decay product $^{56}\mathrm{Co}$, $^{57}\mathrm{Co}$ and $^{44}\mathrm{Ti}$, are expected to form in the deepest layers of the supernova envelope (Timmes et al. 1996). Hence, their final abundances in the ejected envelope may be depleted with respect to the total quantities produced if a significant fraction of these inner layers falls back onto the collapsed core while the explosion is still progressing. In the simplest picture of black hole formation in an otherwise "successful" supernova, larger remnant masses coincide with more fall back and therefore with lower abundances of ejected radioactive isotopes. A quantitative manifestation of this assessment is found in survey by Woosley & Weaver (1995). For a wide range of parameters, they find that explosions which produce remnants with $M_{rem} \gtrsim 3\ M_\odot$ eject negligible abundances of $^{56}\mathrm{Ni}$, while in explosions which leave behind remnants of $1 - 2.5\ M_\odot$, the amount of ejected $^{56}\mathrm{Ni}$ is of order $0.1\ M_\odot$ (the exact value depends on the details of the progenitor and explosion).

2.2.1. *No Radioactive Isotopes*

If we adopt this simple picture of radioactive isotope production in supernovae, we may assume that supernovae which produce black holes eject negligible amounts of radioactive isotopes. Correspondingly, the accretion luminosity must compete only with the thermal emission of the internal energy deposited during the explosion.

Immediately after the explosion the envelope is highly ionized, and therefore opaque to its own thermal photons. The internal energy is emitted slowly through photon diffusion, and the expansion of the envelope is roughly adiabatic, with average density and average temperature falling off inversely with time (Arnett 1996; Zampieri et al. 1998a). Eventually, expansion degrades the envelope temperature sufficiently to allow its material to recombine. The recombined material is practically transparent to the thermal photons, so the envelope cools rapidly. The process is so rapid that the photon distribution cannot adjust to recombination - rather, a recombination "front" sweeps

through the envelope (Arnett 1996), liberating most of its thermal energy.

Recombination sets in after a *recombination time*

$$t_{rec} = t_0(\mathrm{H})\frac{T_0(\mathrm{H})}{T_{rec}(\mathrm{H})} \ , \tag{7}$$

where $T_0(\mathrm{H})$ is the initial average temperature of the hydrogen envelope (which contains most of the mass and the internal energy), $t_0(\mathrm{H})$ is its initial expansion time and $T_{rec}(\mathrm{H})$ is a representative temperature at which hydrogen recombines. Roughly, the internal energy is emitted over a time $\sim t_{rec}$, during which the recombination front sweeps recedes through the bulk of the envelope. We therefore assume that the accretion luminosity emerges at a time of roughly

$$t_{BH} \approx 2t_{rec} \ . \tag{8}$$

This estimate is consistent with observed Type II supernovae (SNeII) light curves, where the time until the recombination peak is roughly equal to the time it lasts until dropping below luminosity from $^{56}\mathrm{Co}$ emission. For example, in SN1987A the recombination peak dominated the light curve between about 50 and 120 days after the explosion; in SN1997D, it appears that the recombination peak lasted between about 40 and 80 days after the explosion. This estimate is also consistent with numerical simulations of SNeII light curves, and, specifically, with our previous simulations of black hole emergence in the absence of radioactive heating (Zampieri et al. 1998a; Balberg et al. 2000).

In the context of our analytic model, we may estimate the recombination time by approximating the entire ejected material (both the helium-rich layer and the hydrogen-rich envelope) as uniform both in temperature and in expansion time, so $T_0(H) = T_0, \ t_0(H) = t_0$. Both quantities can then be expressed in terms of the initial properties of the progenitor, namely the mass of the hydrogen envelope, M_H, and the initial outer radius, R_0:

$$E_{th} = \frac{4\pi}{3}R_0^3 a T_0^4, \ \rightarrow \ T_0 = \left[\frac{3}{4\pi}\frac{E_{th}}{aR_0^3}\right]^{1/4} \ , \tag{9}$$

and

$$t_0 = \frac{R_0}{V_0(\mathrm{H})} = R_0\left[\frac{E_{kin}(\mathrm{H})}{\frac{3}{10}M_\mathrm{H}}\right]^{-1/2} \ . \tag{10}$$

In equations (9-10), E_{th} is the total initial thermal energy in the envelope, while $V_0(\mathrm{H})$ and $E_{kin}(\mathrm{H})$ are the outer velocity and the total kinetic energy of the hydrogen-rich envelope, respectively. Now $E_{kin}(\mathrm{H})$ is defined by our previous parameterization,

$$\begin{aligned} E_{kin}(\mathrm{H}) = \ & E_{kin} - E_{kin}(\mathrm{He}) = \\ & (1-f_\mathrm{He})E_{kin} = (1-f_\mathrm{He})(1-f)E_{exp} \ . \end{aligned} \tag{11}$$

The thermal energy, E_{th}, is some fraction of the kinetic energy, $E_{th} = f_{th}E_{kin}$. To be consistent with the assumption of homologous ballistic expansion, the thermal energy must be significantly lower than the kinetic energy, i.e., $f_{th} \ll 1$; in the following we will use the value $f_{th} = 0.1$. Note that this choice does not necessarily reflect the actual conditions in the supernova at shock break out, when the external radius *is* R_0, since the envelope will not yet have settled into a homologous profile. Rather, it is an effective parameterization of the post-shock flow once it settles into homologous expansion (after a few expansion times; Arnett 1996).

2.2.2. *Some Radioactive Isotopes*

Even relatively low abundances of $^{56}\mathrm{Co}$, $^{57}\mathrm{Co}$ and $^{44}\mathrm{Ti}$ will lead to the tail of the light curve being dominated by radioactive heating. In the case of SN1997D the observed amount of $2\times10^{-3}\ M_\odot$ was found to be sufficient to swamp the accretion luminosity for about 1000 days after the explosion (Zampieri et al. 1998b; Balberg et al. 2000).

It is difficult to generalize the significance of the observed $^{56}\mathrm{Co}$ abundance in SN1997D, since there have been only a handful of other supernovae where the $^{56}\mathrm{Co}$ ($^{56}\mathrm{Ni}$) abundance was observed to be below $0.01\ M_\odot$ (Young et al. 1998), with SN1997D being the only case where this abundance has actually been determined. In view of the importance of radioactive heating to the prospects of observing black hole emergence, we consider several models of the relation between progenitor mass and abundance of radioactive isotopes. We quantify these models through the abundance of $^{56}\mathrm{Co}$, which dominates radioactive heating after recombination ($^{57}\mathrm{Co}$ and $^{44}\mathrm{Ti}$ are discussed below). The black hole emerges in the light curve when the accretion luminosity equals the luminosity due to $^{56}\mathrm{Co}$ heating, $L_{acc}(t_{BH}) = L_{^{56}\mathrm{Co}}(t_{BH})$.

As an extreme model, we examine the possibility that due to mixing in the earliest stages of the explosion a minute amount of radioactive isotopes always reaches the layers which are eventually ejected, regardless of the final black hole mass. Hence we assume that all black hole forming supernovae eject $M_{^{56}\mathrm{Co}} = 2\times10^{-3}\ M_\odot$, as was inferred for SN1997D. As a compromising alternative, we also consider a model where there is always finite $^{56}\mathrm{Co}$ abundance which does depend on the black hole mass: for lack of an actual physical model, we stipulate that $M_{^{56}\mathrm{Co}} = 2\times10^{-3}\ M_\odot$ for $M_{BH} = 3\ M_\odot$, but declines rapidly with increasing black hole mass through the relation

$$M_{^{56}\mathrm{Co}}(M_{BH}) = M_0 \exp\left[-\left(\frac{M_{BH}}{3\ M_\odot}\right)^\beta\right] \ , \tag{12}$$

assuming $M_{BH} \geq 3\ M_\odot$. We consider a "moderate decline" of $\beta = 2$ and a "rapid-decline" of $\beta = 8$. We chose $M_0 = 5.44\times10^{-3}\ M_\odot$, so that $M_{^{56}\mathrm{Co}}(M_{BH} = 3\ M_\odot) = 2\times10^{-3}\ M_\odot$.

At times greater than a few tens of days (when $^{56}\mathrm{Ni}$ decay is complete) the luminosity due to heating from $^{56}\mathrm{Co}$ decays can be estimated as (Woosley et al. 1989)

$$\begin{aligned} L_{^{56}\mathrm{Co}}(t) = & \left(\frac{M_{^{56}\mathrm{Co}}}{M_\odot}\right)\times \\ & \left[\varepsilon_\gamma(^{56}\mathrm{Co})f_\gamma(t) + \varepsilon_{e^+}(^{56}\mathrm{Co})\right]\mathrm{e}^{-t/\tau(^{56}\mathrm{Co})} \ , \end{aligned} \tag{13}$$

where $\varepsilon_\gamma(^{56}\mathrm{Co}) = 1.27\times10^{43}$ ergs s^{-1}and $\varepsilon_{e^+}(^{56}\mathrm{Co}) = 4.45\times10^{41}$ ergs s^{-1}are the energy emission rate in $\gamma-$rays and positrons (produced per $1\ M_\odot$ of $^{56}\mathrm{Co}$), respectively, and $\tau(^{56}\mathrm{Co}) = 111.3$ days is the life time of $^{56}\mathrm{Co}$. The coefficient f_γ includes the effects of a finite optical depth of the envelope to the emitted $\gamma-$energy photons. Photons which escape before thermalizing their energy do not contribute to the bolometric light curve, i.e., $f_\gamma < 1$. Roughly, f_γ can be estimated through the time dependent optical depth of a layer with width $R(t)$:

$$1 - f_\gamma(t) \approx \exp[-\int^{R(t)} \kappa_\gamma \rho(r) dr] \ , \tag{14}$$

where κ_γ is the opacity of the material to the $^{56}\mathrm{Co}$ decay photons; a good estimate is that for the typical energy of these photons, $\kappa_\gamma = 0.03(1+X)$ cm^2 gm^{-1}, where X is the hydrogen

mass fraction of the material. For a uniform density layer with a mass M' and kinetic energy E'_{kin} the $\gamma-$energy photon optical depth can be estimated as (Balberg et al. 2000):

$$\int^{R(t)} \kappa_\gamma \rho(r) dr \approx \kappa_\gamma R_{out}(t)\rho(t) = \kappa_\gamma \frac{3}{4\pi}\frac{3}{10}\frac{M'^2}{E'_{kin}} t^{-2} \ , \quad (15)$$

and we used $R_{out}(t) = V_0 t$ (V_0 is the velocity at the outer edge of the layer) and equation (6). Note that the relation $f_\gamma \propto 1 - \exp(-1/t^2)$ combines with the natural exponential to accelerate the temporal decline of $L_{^{56}\mathrm{Co}}$ (Eq. [13]), much faster than the power-law decline of L_{acc} (Eq. [2]).

2.3. *Summary: Model Parameters and Uncertainties*

The parameterizations introduced above allow to determine the luminosity at emergence as a function of progenitor mass. The key quantity is the effective time t_{dust}:

$$t_{dust} = 2.67 \left(\frac{\mu}{0.5}\right)^{-4/5} \left(\frac{\kappa}{0.4}\right)^{-3/10} \left(\frac{M_{BH}}{M_\odot}\right)^{-1/5} \quad (16)$$
$$\left(\frac{M_{\mathrm{He}}}{M_\odot}\right)^{5/4} \left(\frac{(1-f)E_{exp}}{10^{51}\ \mathrm{ergs}}\right)^{-3/4} \left(\frac{f_{\mathrm{He}}}{0.01}\right)^{-3/4} \quad \mathrm{days}\ .$$

In the following we assume that the composition of the bound material as a mixture in mass of 0.1 hydrogen, 0.45 helium and 0.45 oxygen, which is typical of SNeII models (T. R. Young, 1999, private communication). For this composition $\mu = 1.26$ and $\kappa = 0.22$.

In the case of no radioactive isotopes in the envelope, the emergence time is determined by recombination, and we have

$$t_{BH} = 2t_{rec} = \quad (17)$$
$$138.5 \left(\frac{M_{\mathrm{H}}}{10M_\odot}\right)^{1/2} \left(\frac{R_0}{10^{14}\ \mathrm{cm}}\right)^{1/4} \left(\frac{f_{th}}{0.1}\right)^{1/4} \left(\frac{T_{rec}(\mathrm{H})}{10^4\ {}^\circ\mathrm{K}}\right)^{-1}$$
$$\left(\frac{(1-f)E_{exp}}{10^{51}\ \mathrm{ergs}}\right)^{-1/4} (1-f_{\mathrm{He}})^{-1/4} \quad \mathrm{days}\ .$$

In the case of a finite $^{56}\mathrm{Co}$ abundance, the luminosity due to radioactive heating is estimated with equations (12-13). The $\gamma-$ray optical depth due to the helium-rich layer and the hydrogen-rich envelope is evaluated using equations (14-15). For SNeII we assume that in the helium-rich layer $X = 0.1$ and that in hydrogen-rich envelope $X = 0.7$, giving rise to the following result for the $\gamma-$ray trapping factor:

$$\ln(1 - f_\gamma(t)) = -\left(\frac{t}{300\ \mathrm{days}}\right)^{-2} \times \quad (18)$$
$$\left[1.41 \left(\frac{M_{\mathrm{He}}}{M_\odot}\right)^2 \left(\frac{(1-f)E_{exp}}{10^{51}\ \mathrm{ergs}}\right)^{-1} \left(\frac{f_{\mathrm{He}}}{0.01}\right)^{-1} + \right.$$
$$\left. 2.18 \left(\frac{M_{\mathrm{H}}}{10M_\odot}\right)^2 \left(\frac{(1-f)E_{exp}}{10^{51}\ \mathrm{ergs}}\right)^{-1} (1-f_{\mathrm{He}})^{-1}\right] \ .$$

For most of realistic values of SNeII, the contribution of the helium-rich layer (first term in eq. [18]) dominates $\gamma-$ray trapping, since $M_{He}/M_\odot > M_H/10M_\odot$. However, in the low energy explosions of the most massive progenitors the contribution of the hydrogen-rich envelope becomes comparable, and must be included.

2.4. *Comments on the Model*

The analytic form of equations (16-18) enables us to assess the time of emergence and the corresponding luminosity for a well defined set of assumptions. Naturally, this convenience is achieved at the price of several significant simplifications, and we note some obvious sources of uncertainties.

Homologous Expansion. The assumption of a homologous expansion profile is in itself a crude approximation (see the comparison of an analytic estimate for the emergence time and luminosity with the results of a simulation with a nonhomologous initial profile in Balberg et al. 2000). Furthermore, supernova simulations (see, e.g., Woosley 1988, Shigiyama & Nomoto 1990) also suggest that the helium-rich layer and the hydrogen-rich envelope do not share a common expansion time, but rather $t_0(H) \lesssim t_0(He)$. The ratio of the two tends to be very model dependent. Our model must therefore be treated as illustrative, rather than exact.

Secondary Model Simplifications. The lower mass limit for black holes may be significantly less than $3\ M_\odot$ (Bethe & Brown 1995). In principle this could add many more events, but since lower mass remnants (regardless of nature) are likely to be correlated with larger amounts of radioactive isotopes in the ejecta, they would not make favorable candidates for observing black emergence. Also, there is a small inconsistency since the bound material for late-time accretion is actually included in M_{BH} in the recipe of equation (4). However, since $M_{BH} \geq 3\ M_\odot$ while the amount of bound material for late-time fallback is $0.1 - 0.2\ M_\odot$, the impact of this inconsistency is small. Finally, we note that the estimate of t_{rec} in equation (17) includes two additional parameters, namely the effective thermal energy fraction and the progenitor radius, making the derivation less general. However, since the dependence on both is weak, we do not introduce significant errors by using only representative values for these parameters.

Explosion Energy. Our one parameter model of $L_{BH}(M_*)$ is obviously a simplification, since in reality there should be a range of explosion energies for any progenitor mass. Such a range would be due to rotation, metallicity and other factors which affect progenitor structure and evolution. We aim to accommodate this simplification by conducting a parameter survey with the values of f and f_{He}, which should span a reasonable range of uncertainty in this regard.

Mass Loss. The model does not include potential mass loss, which is expected for massive stars. Mass loss may be important in determining the eventual light curve of the supernova, and perhaps even the properties of the remnant. In this context we distinguish between modest mass loss expected in single stars and the substantial mass loss that occurs in a binary system. In the former the star is likely to retain a sizable fraction of its hydrogen envelope, and so explode as SNII (Willstein & Langer 1999) without a significant effect on the explosion energy and the black hole mass (MacFadyen et al. 1999; Fryer & Kalogera 1999). The more efficient mass loss from massive stars in binaries is actually likely to strip the hydrogen envelope from the progenitors (Willstein & Langer 1999), and if it occurs prior to helium ignition, it may eventually even affect the nature of the explosion and remnant (Fryer & Kalogera 1999), complicating a simple estimate along the lines of our model. However, once the hydrogen envelope is stripped from the star, the likely result will be a Type Ib/Ic supernova, which is unfavorable for detecting black hole emergence (see below). Hence, we can avoid considering the effect of significant mass loss on explo-

sion properties and results. On the other hand, modest mass loss does increase the likelihood that circumstellar interaction and dust formation will obscure the emergence luminosity, and therefore may have an unfavorable effect on the prospect of detecting emergence. We return to this point later in § 4.

Spherical Accretion. We must caution that the results reported here apply strictly for spherical accretion. The assumption of spherical accretion is not necessarily a bad one, since late-time accretion settles after many sound-crossing times, and the flow can recover from modest asymmetries arising in the explosion. Furthermore, unlike accretion in a binary system, the accreting material does not acquire angular momentum from inspiral, and the specific angular momentum is limited to pre-explosion values, which may not be too large. On the other hand, late-time accretion is shaped in part by the luminosity at early times, for which disk-like rather than spherical flow may be more suitable (Mineshige et al. 1997). The radiative efficiency of hypercritical disk accretion is not well constrained by theory, and assessing its implications on the prospects of detecting black hole emergence is beyond the scope of this paper.

3. MODEL RESULTS: LUMINOSITY AT EMERGENCE

With the model of § 2 we proceed to calculate the time of emergence and corresponding luminosity as a function of progenitor mass, $t_{BH}(M_*)$ and $L_{acc}(t_{BH}) \equiv L_{BH}(M_*)$, respectively.

3.1. *Emergence Luminosity with no Radioactive Isotopes*

The most favorable situation for observing black hole emergence, is when radioactive heating is negligible and emergence occurs once envelope recombination stratifies. The results for the accretion luminosity (Eq. [2]) based on the effective time t_{dust} (Eq. [16]) and emergence time, t_{BH} (Eq. [17]) as a function of progenitor mass are shown in Figure 2. In the calculations we varied the fraction of explosion energy spent on unbinding the star ($f = 0.25,\ 0.50$ and 0.75), and the fraction of kinetic energy deposited in the helium layer ($f_{\rm He} = 0.01$ and 0.03). We set the progenitor radius at $R_0 = 5 \times 10^{13}$ cm and the fiducial fraction of thermal energy as $f_{th} = 0.1$.

The accretion luminosities at emergence varies between several 10^{35} to 3×10^{37} ergs s^{-1}for the most optimistic models. The results are quite sensitive to both effective parameters f and $f_{\rm He}$, and, for a given progenitor mass, can vary by more than an order of magnitude between extreme assumptions. In spite of these uncertainties, we can identify some global trends. First, for a given total explosion energy and black hole mass (given value of f), the luminosity at emergence increases with decreasing $f_{\rm He}$: less energy to the helium layer means more bound mass which is also slowly moving as a reservoir for late-time accretion. Within the parameterization of the model, $t_{dust} \propto f_{\rm He}^{-3/4}$ while t_{BH} is very weakly dependent on $f_{\rm He}$, thereby yielding the relation $L_{BH} \propto f_{\rm He}^{75/72}$, which holds for progenitors of all masses.

The luminosity at emergence also increases with increasing f, and that the sensitivity to this factor is at least as large as that to $f_{\rm He}$. Although a larger available energy for unbinding the star leads to a lower mass black hole, it implies a larger helium-rich layer in the ejecta and less kinetic energy for the ejecta (which scales as $1-f$). In the parameterization equations (2) and (16-17) a thick and slow helium-rich layer (i.e., a larger reservoir of material for late-time accretion) outweighs

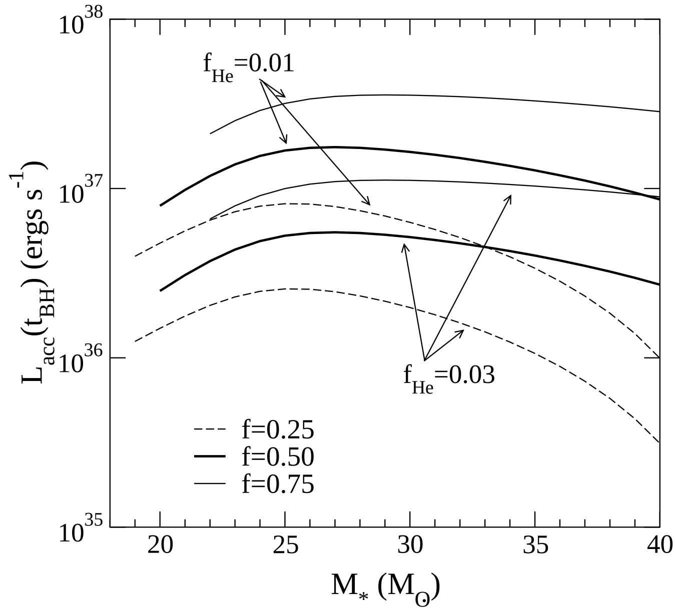

FIG. 2.— Parameter survey for the accretion luminosity at emergence, L_{BH}, as a function of progenitor mass, M_*, for the model with no radioactive heating. Parameters surveyed are f and $f_{\rm He}$, with $f = 0.25,\ -$ dashed lines, $f = 0.50$ $-$ thick solid lines, and $f = 0.75$ $-$ thin solid lines, and with $f_{\rm He} = 0.01$, and 0.03.

the mass of the black hole in determining the magnitude of the accretion luminosity. For realistic values of f we find that roughly $L_{BH} \propto f$. This result reinforces previous expectations (Zampieri et al. 1998a; Balberg et al. 2000) that supernovae with low inferred explosion energies (low expansion velocities) are the most promising in terms of observing black hole emergence. Note that since the actual values of black hole and helium-layer masses also depend on the progenitor mass, changing f does not just scale the $L_{BH}(M_*)$ curve (as changing $f_{\rm He}$ does) but also modifies the shape of this function. The dependence of emergence luminosity on progenitor mass can also be understood in terms of the competition between black hole mass and ejected helium layer mass.

3.2. *Emergence Luminosity with Radioactive Heating*

If radioactive decays dominate over accretion as the heating source after recombination, emergence can be significantly delayed. We determine emergence time and luminosity by comparing the evolution of the accretion luminosity (eqs. [2] and [16]) and the radioactive luminosity (eqs. [13] and [18]) for a given $M_{^{56}\rm Co}$ (eq. [12]) in the ejecta. The emergence luminosity as function of progenitor mass, $L_{BH}(M_*)$, is shown for three combinations of f and $f_{\rm He}$ in Figure 3; these are $\{f = 0.5\ \ f_{\rm He} = 0.01\}$, $\{f = 0.75\ \ f_{\rm He} = 0.01\}$ and $\{f = 0.25\ \ f_{\rm He} = 0.03\}$, which are intermediate, most optimistic and least optimistic, respectively, in terms of the accretion luminosity they predict. In each case we compare four assumptions about the abundance of ^{56}Co : none (i.e., the results in § 3.1), $M_{^{56}\rm Co} = 2 \times 10^{-3}\ M_\odot$ for all progenitors, and a black hole mass-dependent abundance according to equation (12), with $\beta = 2$ and 8 (labeled with the value of β).

The dominant feature of Figure 3 is that the qualitative effect of including radioactive heating is similar for all three cases (and, indeed, is similar for other combinations of f and $f_{\rm He}$ not shown here). When a constant $M_{^{56}\rm Co} = 2 \times 10^{-3}\ M_\odot$ is assumed for all progenitor masses, the emergence luminosity is decreased by a factor of 5-50 with respect to its value in

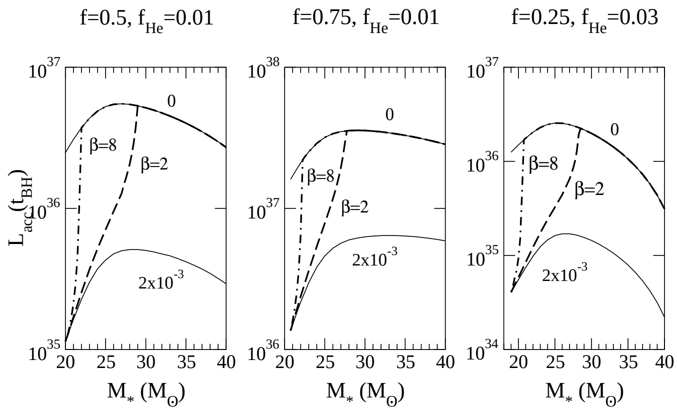

FIG. 3.— Accretion luminosity at emergence, L_{BH}, as a function of progenitor mass M_* for three combinations of f and $f_{\rm He}$ and different assumptions about the abundance of ^{56}Co in the ejected envelope. Curves are labeled with the mass of $M_{^{56}{\rm Co}}$ if independent on M_* and by the value of β used for a $M_{^{56}{\rm Co}}(M_*)$ according to its value in equation (12).

the radioactive-free case for the same $\{f,\ f_{\rm He}\}$ combination; a greater decrease corresponds to a lower value of L_{BH} in the radioactive-free case. This similarity results because the time of emergence is controlled by the exponential decline of the ^{56}Co heating rate; the emergence times are then constrained to the rather narrow range of 1200 ± 200 days, hence constraining the value of L_{BH} as well.

When the amount of ^{56}Co is assumed to decline with increasing black hole mass, the L_{BH} curve ascends from the $M_{^{56}Co} = 2 \times 10^{-3}\ M_\odot$ values for lower mass progenitors to the radioactive-free values for higher mass progenitors; the slope of this ascent is, of course, determined in our parameterization by the value of β. The net effect of such a black hole mass-dependent ^{56}Co abundance is to suppress the contribution of the lower mass range of progenitors to observable black hole emergence events. The implications of this suppression on the rate of observable events of black hole emergence may be quite significant, if a realistic progenitor mass distribution is weighted towards the lower mass stars, these progenitors dominate the supernova rate.

It is important to comment on the implications of ^{57}Co and ^{44}Ti . If those isotopes are present with abundances which scale with $M_{^56{\rm Co}}$ similar to the ratios inferred in SN1987A (Woosley & Timmes 1996), they would dramatically alter the prospects for observing black hole emergence. It is unclear to what extent such scaling is justified, since ^{57}Co and ^{44}Ti are synthesized even deeper than ^{56}Ni , so scaling is mostly useful for placing an upper limit on the ^{57}Co and ^{44}Ti abundances. If these abundances do scale according to $M_{^{56}{\rm Co}} = 2 \times 10^{-3}\ M_\odot$ and the SN1987A ratios, both become important for radioactive heating at about 1000 days after the explosion (Balberg et al. 2000), with heating rates of $L_{^{57}{\rm Co}} \approx L_{^{44}{\rm Ti}} \lesssim 10^{35}$ ergs s^{-1}. Heating from ^{44}Ti decay (positron heating) should remain at this level for tens of years after the explosion. Thus, if L_{BH} estimated from comparison with $L_{^{56}{\rm Co}}$ is slightly less than a several 10^{35} ergs s^{-1}, unveiling the accretion luminosity would be a more difficult task since the total luminosity will include additional components (rather than follow a simple power law decay). If L_{BH} is significantly less than 10^{35}ergs s^{-1}, as in the case of $f = 0.25$ $f_{\rm He} = 0.03$ and $M_{^{56}{\rm Co}} = 2 \times 10^{-3}\ M_\odot$, the accretion luminosity would be sufficiently subdominant so that detection would be impossible. Fortunately, we can avoid detailed investigation of the effects of ^{57}Co and ^{44}Ti since for HST capabilities an emergence luminosity below 10^{35} ergs s^{-1}cannot be detected beyond the Local Group (see below). Provided that scaling of ^{57}Co and ^{44}Ti abundances as in SN1987A applies, any emergence luminosity that is low enough to be obscured by ^{57}Co and ^{44}Ti heating is undetectable in any case.

4. RATE OF OBSERVABLE BLACK HOLE EMERGENCE

Having derived the function $L_{BH}(M_*)$, we now proceed to estimate the event rate. We define an "event" in this context as a case where the accretion luminosity at emergence is above the threshold of a given instrument (the total luminosity is twice as large, of course, but we assume conservatively that a factor of two margin would be needed to certify the nature of the accretion luminosity, especially if the power-law dependence is to be identified). The detector threshold translates into a minimum emergence luminosity which can be detected from any given distance. We will use the HST STIS camera capabilities as a our reference and require a threshold apparent bolometric magnitude of $m_B = 28.5$. The function $L_{BH}(M_*)$ provides the progenitor masses which have emergence luminosity exceeding that minimum luminosity; their relative fraction out of all progenitors which make core collapse supernovae is determined by assuming a present day mass function (PDMF) of progenitors. In this section we estimate this fraction and compare it with the observed supernova rate in the local universe in completing an estimate of events of observable black hole emergence.

4.1. *Events per Supernova as a Function of Distance*

For simplicity, we assume a single power law PDMF for the progenitors of core collapse supernova, similar to the initial mass function (IMF) of the Milky Way. There is some observational evidence the mass function of massive stars in the Milky Way does follow such a power law with no sign of dependence on metallicity (Massey & Thompson 1991). In this parameterization, the fraction $F(M)$ of progenitors with mass greater than M follows the relation

$$\frac{dF}{dM} \propto M^{-\gamma}\ ; F(M) = C_{cc} M^{-\gamma+1}\ ; \qquad (19)$$
$$C_{cc} = (M_1^{-\gamma+1} - M_2^{-\gamma+1})^{-1}\ ,$$

where the value of the constant C_{cc} arises from stipulating that core-collapse supernovae occur in stars with progenitor masses between M_1 and M_2.

We also assume that all local galaxies which host core-collapse supernovae share a single power law γ. By changing

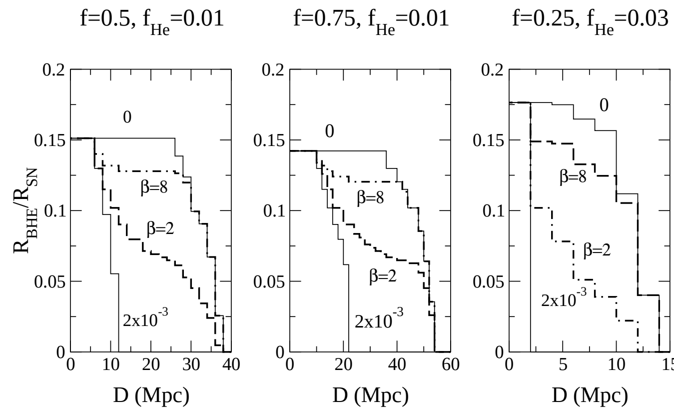

FIG. 4.— The fraction of Type II supernovae for which black hole emergence can be observed as a out of the all Type II supernovae as a function of distance for three combinations of f and $f_{\rm He}$ and the various assumptions about the ^{56}Co abundance (see Fig. 3) and $\gamma = 2.7$.

γ over a reasonable range of values we can assess the likely uncertainties embedded in this assumption. The value of γ is crucial in determining the black-hole-per-core-collapse-supernova fraction, which is essentially the fraction of progenitors which leave behind a remnant with $M \geq 3\ M_\odot$. By following Fryer & Kalogera (1999) who adopted the Scalo (1986) value of $\gamma = 2.7$ as a nominal choice and assumed core collapse supernova occur for progenitors with masses in the range $8 - 40\ M_\odot$, we find that the fraction of supernovae which make black holes is about 0.15.

The combination of the function $L_{BH}(M_*)$ and the PDMF of progenitors allows to estimate what is the fraction of black hole forming supernovae for which emergence is observable as a function of distance. It can be further expanded to estimate the fraction of emergence events out of all core-collapse supernovae (most of which produce neutron stars). In Figure 4 we show this fraction as a function of distance from the Milky Way, (for a threshold apparent magnitude of 28.5), assuming no dust extinction along the line of site. The three graphs correspond to the three combinations of f and $f_{\rm He}$ shown in Figure 3, with each case including the different assumptions concerning the abundance of ^{56}Co . The results are binned in 2 Mpc intervals.

At very close distances, all supernovae which create black holes yield an observable emergence, so the "event" per supernova rate is simply the fraction of supernovae which make black holes. The characteristic fraction of $\sim 15\%$ for $\gamma = 2.7$ does have some dependence on the value of f, which determines the threshold progenitor mass for producing a black hole. As distance is increased, for some progenitor masses the emergence luminosity falls below threshold and the event fraction (out of all supernovae) decreases. The significance of radioactive heating is clearly evident in the details of each graph, where a larger $M_{^{56}{\rm Co}}$ naturally delays the emergence of the black hole, and so the luminosity at emergence is lower and therefore is observable over smaller distances. The importance of the distinction between the two exponential cases, $\beta = 2$ and $\beta = 8$ is also evident. For $\beta = 8$ radioactive heating does not affect the maximum values of L_{BH} so the dominant contribution to cases of observable emergence, especially at large distances, is similar for the radioactive-free case and the $\beta = 8$ case. On the other hand the $\beta = 2$ model results in reducing the maximum value of L_{BH}, thereby reducing the maximum distance, D_{max}, of observable emergence.

Most notable is the difference between typical distances over which emergence is observable for the different combinations of f and $f_{\rm He}$. These vary from $D_{max} \approx 14$ Mpc for the worst case $\{f = 0.25\ f_{\rm He} = 0.03\}$ (and radioactive free) to $D_{max} \approx 54$ Mpc for the best case $\{f = 0.75\ f_{\rm He} = 0.01\}$, which roughly amounts to a factor of about 60 in volume, and hence in the event rate. In general, we find that the combination of the uncertainty in f and $f_{\rm He}$ and in the abundance of ^{56}Co places D_{max} roughly in the range of $10 - 50$ Mpc, corresponding to a span in the expected event rate of two orders of magnitude. In this last assessment we exclude the case of $\{f = 0.25\ f_{\rm He} = 0.03\}$ and $M_{^{56}{\rm Co}} = 2 \times 10^{-3}\ M_\odot$ for which black hole emergence is essentially unobservable beyond the Local Group. Recall that this is also the combination where the accretion luminosity may be obscured if the amount of ^{57}Co and ^{44}Ti is not negligible. If this extreme combination is representative of black hole forming supernovae, the rate of observable emergence is very small.

The slope of the PDMF, γ, has some influence over the fraction of black hole-forming supernovae and over the observable event rate. For values of γ between 2 and 3, the fraction of core-collapse supernovae which form black holes varies between 0.25 and 0.125, respectively. The point is that the value of γ does not affect the maximum distance for observation for a given $\{f\ f_{\rm He}\}$ model. Figure 5 compares the event per core collapse supernova fraction for $\{f = 0.5\ f_{\rm He} = 0.01\}$ for $\gamma = 2,\ 2.7$, and 3. In all cases the fraction at any given distance approximately follows the total fraction of progenitors which make black holes. Note that the graphs for $\gamma = 2$ and $\gamma = 3$ are almost identical, after the y-axes are scaled 2:1.In total, the uncertainty in γ accounts for a relatively modest uncertainty of a factor of 2 in the event rate.

An additional modest source of uncertainty is the lower limit on progenitor masses which make core collapse supernovae. For $\gamma = 2.7$, stars between 8 and 10 $M_\odot$ make up about one third of all those between $8 - 40\ M_\odot$, so the fraction of supernovae from higher mass progenitors out of the total could be sensitive to our choice of the lowest mass progenitors by as much as 50%. On the other hand, unless the PDMF is exceptionally flat, the exact value of the upper mass limit is not too important, since stars at the very high mass end are very rare.

4.2. *Eliminating Type Ib/c Supernovae*

So far we referred to estimates of the event rate per core-collapse supernova, which is the expected fate of massive progenitors. These include also Type Ib/c supernovae which are not good candidates for observing black hole emergence (Balberg et al. 2000): if the hydrogen envelope has been ejected prior to explosion, practically all the kinetic energy is deposited

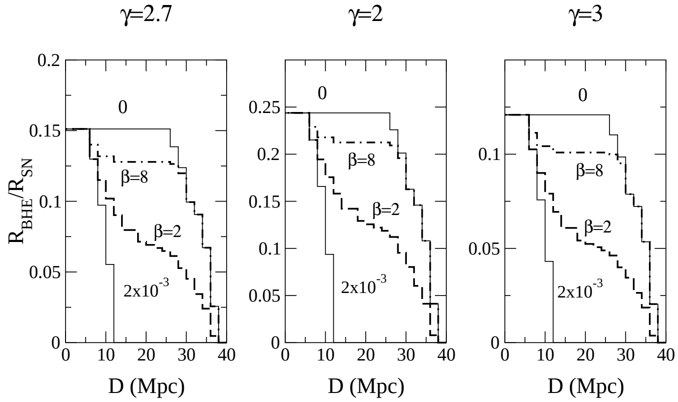

FIG. 5.— The fraction of Type II supernovae for which black hole emergence can be observed as a out of the all Type II supernovae as a function of distance for for $\gamma = 2.7$ (nominal) and 2 and 3, the various assumptions about the ^{56}Co abundance (see Fig. 3), and $\{f = 0.5\ f_{\rm He} = 0.01\}$.

in the helium layer ($f_{\rm He} = 1$). Effectively, the evolutionary option of a Type Ib/c supernova reduces the fraction of core collapse supernovae in which black hole emergence could be observable.

Studies of single and binary stellar evolution indicate that the likelihood that sufficient mass loss will occur during the life time of a massive star depends mainly on the presence and properties of a binary companion; the mass of the star appears to play a secondary role. In our analysis we use the simplest classification offered by Willstein & Langer (1999), where massive stars in binaries lose all their hydrogen envelope and result in a Type Ib/Ic supernova, and single massive stars do not lose all of the envelope, giving rise to a SNII. This simplest interpretation is that the probability of a massive star yielding a SNII, P_{II}, is independent of its mass. With this assumption, the calculations of the fractions shown in Figures 4-5 are then the fractions *per SNII*, related to the fraction *per core-collapse supernovae* by a factor of P_{II}. In the following we will set $P_{II} = 0.85$, which is roughly consistent with theoretical estimates of supernova rates (Thielemann 1994; Cappellaro et al. 1997).

4.3. *Rate of Events in the Local Universe*

If the efficiency of discovering supernovae in the local universe ($D \approx 50$ Mpc) were perfect, event-per-supernova fractions such as those shown in Figure 4 should be compared to the estimated supernova rate per galaxy. These are somewhat constrained based on observation and theory, and generally expressed in units of SNu (1SNu = supernovae per century per $10^{10}\ L_\odot$). The estimated rates (Thielemann 1994; Cappellaro et al. 1997) are dependent upon galaxy type, where core collapse supernovae appear to be limited to spiral and irregular galaxies. The combined theoretical rates (in SNu) for spiral galaxies are: SNeII - about 0.7 ± 0.3, and Type Ib/c - about 0.14 ± 0.07 (with some dependence on specific galaxy type). In irregular and peculiar galaxies there appears to be a slightly larger fraction of Type Ib/c supernovae (SNeIb/Ic), whereas in elliptical there are hardly any core collapse supernovae at all.

However, the actual constraint on observing black hole emergence rate is the rate at which supernovae are *discovered*, rather than the rate at which they occur. Clearly, any attempt to uncover the emergence of the black hole would be conditional on the supernova being found in the first place. The efficiency of discovering supernovae is imperfect due to both incomplete monitoring of the sky and line of sight limitations (background, extinction etc.). For example, unfavorable inclination of the host galaxy appears to cause a deficiency of observed supernova in galactic cores with respect to those found which are offset from the galactic centers (Cappellaro et al. 1997).

4.3.1. *Rate of Observed Supernovae*

A recent compilation of supernovae catalogs (Barbon et al. 1999) suggests that the recent (1997-1998) rate of *observed* supernovae identified as core collapse in the local universe is roughly 10^{-4} Mpc^{-3} yr^{-1} although the uncertainty in this estimate is quite large. This number includes both SNeII and SNeIb/Ic, with a ratio of about 5:1, respectively. Within the statistical uncertainties of the search, these rates appears to be independent of distance up to 50Mpc. Such distance-independence arises from the limits of supernovae searches (incomplete coverage of the sky, methods of the searches), which currently dominate over the dimming of the more distant supernovae. A rate of 10^{-4} Mpc^{-3} yr^{-1} is roughly 10-20% of the total rate of core collapse supernovae which are expected to occur in the local universe.

While we will use this estimate of 10^{-4} Mpc^{-3} yr^{-1} core collapse supernova as a guideline in our calculation, it is clear that at very small distances any approximation of a uniform observed supernova rate must break down. In particular, the actual supernova rate up to several Mpc from the Milky Way is dominated by a few individual galaxies: most notably, the star burst galaxies NGC 253 (3.0 Mpc) and M82 (3.5Mpc). We rely on the estimates of Becklin (1991), who evaluated the core-collapse supernova rate up to 12 Mpc from the properties of observed galaxies. His estimate was based on a rather high theoretical rate of core collapse supernovae: 6 per century per $10^{10}\ L_\odot$ in IR (the contribution of massive stars to IR emission exceeds that in optical). Recent surveys seem to favor a rate which is about one half of that. We therefore modify those estimates by a factor of 0.5. The rates of core collapse supernovae that we use for this range are: 2-4 Mpc - 0.3yr^{-1}; 4-6 Mpc - 0.02yr^{-1}; 6-8 Mpc - 0.4yr^{-1}; 8-10 Mpc 0.15yr^{-1}; and 10-12 Mpc - 0.3yr^{-1}. This last value fits onto the estimated observed rate of 10^{-4} Mpc^{-3} yr^{-1} assumed to hold beyond these closest distances. We do not include here supernovae in the Local Group (0-2 Mpc), since they are dominated by the Milky Way and for the most part would be unobservable.

4.3.2. *The Rate of Observable Black Hole Emergence Events*

We first assume naively that the probability of detection of a SNII is independent of progenitor mass (hereafter the UNBIASED model). The event fraction per *occurring* core collapse supernova in § 4.1 then translates simply into an event fraction

per *observed* core collapse supernovae. Using the estimates for the observed rate above, we then calculate the total rate of observable black hole emergence events, including a factor of 0.85 to count only SNeII where emergence is observable. These estimated rates as a function of f, $f_{\rm He}$ and the assumptions regarding the ^{56}Co abundance are shown in Table 1.

TABLE 1
PREDICTED RATES (YR^{-1}) FOR OBSERVABLE BLACK HOLE EMERGENCE IN THE "NAIVE" MODEL (SEE TEXT).

f	$f_{\rm He}$	$M_{^{56}\rm Co} =$ 0	$M_{^{56}\rm Co} =$ $2\times10^{-3}\ M_\odot$	$\beta = 2$ (Eq. [12])	$\beta = 8$ (Eq. [12])
0.25	0.01	0.72	0.06	0.28	0.64
0.25	0.03	0.23	~ 0	0.08	0.19
0.50	0.01	2.05	0.17	0.97	1.89
0.50	0.03	0.43	0.05	0.19	0.37
0.75	0.01	5.74	0.44	3.45	5.36
0.75	0.03	1.06	0.13	0.58	0.97

The results in Table 1 indicate that the likely rate of detecting of black hole emergence in supernovae in nearby galaxies clearly depends on all three of our main unknowns - the fraction of energy spent on unbinding the stars, distribution of kinetic energy between the hydrogen envelope and the helium layer, and the abundance of ^{56}Co . Within the limits we used in our models, each parameter alone imposes an uncertainty of a factor of a few in the event rate, whereas the combined effect of all three accumulates to about two orders of magnitude of uncertainty. The prediction for the event rate varies between as many as a few events per year to a few events per century. In the former case, one expects that several of the SNeII discovered each year will lead to an observable black hole emergence, were they to be monitored for months after the explosion. Note that for most of the parameter range, the event rate should at least be one event every few years; rates lower than that are confined almost uniquely to the worst case model for radioactive heating, when a constant $M_{^{56}\rm Co} = 2\times10^{-3}\ M_\odot$ for all supernovae is assumed.

4.3.3. *Effects of Bias in Observability of Supernovae and Emergence*

The estimates above may be too naive in their prediction of the rate of observable events of black hole emergence, since it explicitly assumes that all SNeII are equally likely to be detected. A more realistic point of view is that the probability of detecting SNeII is not uniform, but rather is dependent on its peak luminosity. Recall that the best known candidate for observing black hole emergence, SN1997D, is considered significantly subluminous in comparison with typical SNeII. While it is unlikely that underluminous supernova dominate the total supernova rate (Cappellaro et al. 1997 limit them at $20-30\%$ of the total rate), they may represent a large fraction of the black hole forming explosions. If, on average, black hole forming supernovae have a lower probability of being discovered, the fraction of events per observed SNII is obviously reduced with respect to our first estimate.

The luminosity of supernovae during the diffusion and recombination phase is known to depend on the explosion energy and progenitor radius and structure (Arnett 1996), and indeed, observations indicate a heterogeneous luminosity distribution. In particular, relatively compact progenitors will result in an underluminous light curve even if the explosion energy was quite large, as was the case in the very well studied SN1987A. Nonetheless, it is reasonable to expect some correlation in the detectability of supernovae with explosion energy. For lack of a better model, we assume that the probability of detecting the supernova is proportional its typical luminosity. We further assume that this typical luminosity is proportional to explosion energy deposited in the envelope (i.e., to $(1-f)E_{exp}$ in our parameterization). This approximation is roughly correct for a given progenitor (Arnett 1996; Balberg et al. 2000). We show the quantitative effect of such a bias against detecting low luminosity supernovae on the resulting fractions of event per observed SNII as a function of distance in Figure 6b, for $\gamma = 2.7$, $\{f = 0.50\ f_{\rm He} = 0.01\}$ and after normalizing the fraction of all observed supernovae in the range $8-40\ M_\odot$ to unity. The immediate result in this model (hereafter the E-BIAS model) is a significant reduction of the typical fraction of event per observed supernova, which is now down to about 0.02 instead of 0.15. Also, the relative impact of the bias is larger in the cases with a progenitor mass dependence of the ^{56}Co abundance. This is quite expected, since in these cases the effect of ^{56}Co is limited to the lower mass progenitors, so the relative contribution of the higher mass progenitors in the event is greater. The corresponding predicted rates under this E-BIAS model for the various $\{f\ \ f_{\rm He}\}$ combinations are shown in Table 2.

TABLE 2
PREDICTED RATES (YR^{-1}) FOR OBSERVABLE BLACK HOLE EMERGENCE IN THE MODEL WITH AN EXPLOSION ENERGY BIAS (SEE TEXT - MODEL E-BIAS).

f	$f_{\rm He}$	$M_{^{56}\rm Co} =$ 0	$M_{^{56}\rm Co} =$ $2\times10^{-3}\ M_\odot$	$\beta = 2$ (Eq. [12])	$\beta = 8$ (Eq. [12])
0.25	0.01	1.51×10^{-1}	9.83×10^{-3}	4.02×10^{-2}	1.24×10^{-1}
0.25	0.03	4.91×10^{-2}	~ 0	9.90×10^{-3}	3.65×10^{-2}
0.50	0.01	2.80×10^{-1}	2.22×10^{-2}	9.56×10^{-2}	2.40×10^{-1}
0.50	0.03	5.90×10^{-2}	5.08×10^{-3}	1.78×10^{-2}	4.69×10^{-2}
0.75	0.01	3.76×10^{-1}	9.83×10^{-2}	1.72×10^{-1}	3.32×10^{-1}
0.75	0.03	6.98×10^{-2}	8.65×10^{-3}	2.91×10^{-1}	6.02×10^{-2}

Overall, we find that biasing the supernova detection probability according to explosion energy has a profound effect on the expected rate of observable black hole emergence. In general, we find that the event rate drops by a factor of 5-15 with respect to an unbiased detection probability, as depicted in Table 1. Note that the effect is more pronounced for larger values of f, because the luminosity is driven by the energy that is not spent on unbinding the star, i.e., on $1-f$. The typical event rates with these revised assumption are mostly once per several years for $f_{\rm He} = 0.01$ and once per tens of years for $f_{\rm He} = 0.03$. Once again, a constant $M_{^{56}\rm Co} = 2\times10^{-3}\ M_\odot$ for all progenitors would be especially destructive in terms of decreasing the potential event rate.

An additional source of potential bias that would reduce the observability of black hole emergence is luminosity due to interaction of the ejected envelope with circumstellar material (CSM). If the CSM is dense enough, a significant luminosity, L_{CSM}, will arise as the shock wave propagates through it. Interaction with the CSM is the preferred model for the subclass SNeIIn, which are characterized by a high, slowly decaying, luminosity after the recombination peak. In particular, Chevalier & Fransson (1994) demonstrated that a dense CSM could sustain a luminosity at a level of $L_{CSM} \approx 10^{40}$ ergs s^{-1}for several hundred years after the explosion. A luminosity at this level would black hole would obscure any potential accretion luminosity. Indeed, this was quite possibly the case for SN1994W (Sollerman et al. 1998), which otherwise could have been a

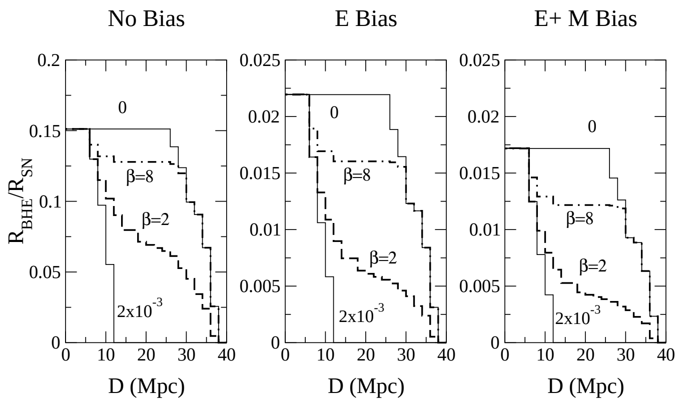

FIG. 6.— The fraction of *observable* Type II supernovae for which black hole emergence can be observed as a function of distance out the total number of *observable* Type II supernovae for three sets of assumptions about supernova observability and accretion luminosity. These are (from left to right) - UNBIASED: (same as left panel in Fig. 4); E-BIAS: underdetection of low energy explosions, and E+M-BIAS: underdetection of low energy explosions combined with CSM obstruction of black hole emergence (see text). In all cases $f = 0.5$, $f_{\rm He} = 0.01$ and $\gamma = 2.7$; all variations for the ^{56}Co abundance are shown (see Fig. 3).

promising candidate for observing black hole emergence. Cappellaro et al. (1997) estimated that Type IIn supernovae are relatively rare, and probably make up only $2-5\%$ of the total SNeII rate. However, they note that owing to the relatively high luminosities of these supernovae, in recent years their contribution to the *observed* rate of SNeII is $15-20\%$; their influence over the present study must therefore be examined. Moreover, since the CSM is essentially the residue of mass loss from the progenitor during the red giant phase, more massive progenitors are more likely to have produced denser CSM.

While the rate of mass loss in the star's wind, $\dot{M}_{wind}$, is expected to increase with progenitor mass, many other factors will contribute to the overall properties of the wind and the resulting CSM. We note that there was no evidence of CSM interaction at any stage in the observation of SN1997D (Benetti et al. 2001). For the purpose of a quantitative estimate of the potential influence of CSM interaction on the prospects of observing black hole emergence, we assume that the probability of the accretion luminosity *not* being obscured by a high L_{CSM} decreases for larger progenitors and scales as $M_*^{-\theta}$. We calibrate θ by imposing the following combination: assume that (a) significant L_{CSM} occurs in 5% of SNeII and that (b) if all supernovae with CSM interaction are observed, they make up 20% of observed SNeII. Imposing these assumptions on the E-BIAS model described above, we find that for $\gamma = 2.7$ this combination is best reproduced with $\theta \approx 0.5$. By including the effect of possible CSM interaction on the light curve according to this recipe and renormalizing the overall observed SNeII rate, we arrive at yet another set of event per observed SNeII fractions as a function of distance (hereafter the E+M-BIAS model). These sets are presented in Figure 6c. Note that these new fractions are naturally lower than the corresponding values in the E-BIAS model. The total predicted rates under these assumptions are given Table 3.

Quantitatively, the potential of CSM interactions contributes an additional effect of reducing the predicted event rates by $\sim 30\%$ with respect to Table 2. It also further reduces the event rate in the $\beta = 8$ model with respect to the radioactive free one, emphasizing the significance of even a small abundance of ^{56}Co in the lower mass progenitors. While the additional mass dependent bias is not as important as the explosion energy bias, owing to the different functional dependence on M_*, the effect of CSM interactions - as parameterized in our model - reduces the rate of observable black hole emergence to, at best, one per four years. For most of a parameter range, we conclude that with using HST capabilities and current limits of supernova searches this rate is probably not better than once per decade.

TABLE 3

PREDICTED RATES (YR^{-1}) FOR OBSERVABLE BLACK HOLE EMERGENCE IN THE MODEL WITH AN EXPLOSION ENERGY AND WIND BIAS (SEE TEXT - MODEL E+M-BIAS).

f	$f_{\rm He}$	$M_{^{56}{\rm Co}} = 0$	$M_{^{56}{\rm Co}} = 2\times10^{-3}\ M_\odot$	$\beta = 2$ (Eq. [12])	$\beta = 8$ (Eq. [12])
0.25	0.01	1.21×10^{-1}	7.49×10^{-3}	2.94×10^{-2}	9.73×10^{-2}
0.25	0.03	3.95×10^{-2}	~ 0	6.99×10^{-3}	2.85×10^{-2}
0.50	0.01	2.16×10^{-1}	1.72×10^{-2}	6.86×10^{-2}	1.82×10^{-1}
0.50	0.03	4.58×10^{-2}	3.72×10^{-3}	1.26×10^{-2}	3.55×10^{-2}
0.75	0.01	2.84×10^{-1}	2.01×10^{-2}	1.22×10^{-1}	2.47×10^{-1}
0.75	0.03	5.29×10^{-2}	6.52×10^{-3}	2.06×10^{-2}	4.48×10^{-2}

5. CONCLUSIONS AND DISCUSSION

In this work we attempt a first estimate of the rate at which black hole emergence in supernovae may be observed. We used an analytic model and a parameter survey to examine the competition between the expected accretion luminosity and the other sources of power for the supernova light curve, most notably radioactive heating. In general, we show that the event rate is larger if the relative fraction of the total kinetic energy driving the expansion (not spent on unbinding the star) is smaller and if the fraction of this kinetic energy deposited in the helium layer (which is the source of late-time accretion) is also smaller. Furthermore, the event rate is larger for reduced amounts of radioactive heating in the envelope.

With the efficiency of current supernova searches and the capabilities of the HST for detecting the accretion luminosity at emergence, we find that under optimistic assumptions, the rate of "events" – successful observations of black hole emergence – may be as large as a few events per year. If Type II supernovae in current searches are detected with no dependence on progenitor mass and explosion energy, then for most of our parameter range, the event rate should be better than once per two years. However, in the more likely event that detection of supernovae in current searches is weighted towards brighter supernovae, this rate is dramatically reduced. The more massive progenitors which lead to black hole formation are also likely to produce less luminous explosions, and would therefore be underrepresented in present searches. The best known potential candidate for allowing observable black hole emergence, SN1997D, was such a subluminous explosion. If a bias

against discovering supernovae from explosions of more massive progenitors exists, it reduces the potential rate of finding black hole emergence in supernovae as well. We estimate that the event rate in the presence of such a bias is not larger than once per few years. We also find that some additional bias may arise due to obstruction of the accretion luminosity by interaction of the expanding envelope with circumstellar material. Such obstruction is more likely for the more massive progenitors which experience greater winds during their evolution; we view SN1994W as a likely candidate for potential emergence that was obscured by luminosity due to circumstellar interaction. We find that if probability of significant contribution to the light curve from interaction of the ejecta with circumstellar material is larger for more massive progenitors, the fraction of observable black hole emergence per observed Type II supernovae is reduced by an additional factor of $0.3 - 0.7$. In this later case the actual event rate for present detection capabilities and limitations of supernovae searches is unlikely to be greater than one per decade.

Our findings suggest that, at present, the prospects of observing black hole emergence in Type II supernovae are small, but not negligible. The immediate consequence is that if a low energy Type II supernova is discovered, high priority must be given to following it for several months until beyond recombination. If a small ($\sim 10^{-3}\ M_\odot$ or less) amount of $^{56}\mathrm{Co}$ is then identified in the tail of the light curve, it would be prudent to schedule HST observations of the declining light curve with hope of observing the emergence of the black hole.

These rates might be somewhat increased by detailed spectral analyses, although a successful spectral analysis requires a larger-than-threshold total luminosity. Since luminosity due to radioactive heating and CSM interaction is generated in the outer (and cooler) part of the expanding envelope, their spectra tend to be mostly in the R-band. Furthermore, in typical Type II supernovae the light curve is observed to become redder at later times, as the effective temperature of the emitting region decreases. By contrast, the accretion luminosity is generated deep in the ejecta, so its effective temperature should be that of partially ionized envelope material - 5000-10000 degrees. Frequency-dependent calculations of the accretion luminosity have not been carried out, but the intensity should peak in the visible or near IR. A light curve in which the R-band luminosity follows a decline rate expected from $^{56}\mathrm{Co}$ decay while the visible band luminosity appears to be decline more slowly could indicate the presence of the black hole even if accretion is still subdominant in the total bolometric luminosity.

Perhaps the most important conclusion of our analysis is that detectability of the supernovae themselves appears to be the dominant factor in the rate of observing black hole emergence, if indeed black hole producing supernovae are fainter than average. Clearly, a search for black hole emergence will benefit greatly from any dedicated faint supernova project, indirectly also from one aimed at high red shift explosions. If the bias we assumed against discovery of fainter supernovae (Table 2) can be at least partially lifted by such a search, we may be able to approach the higher rates found for an unbiased survey (Table 1). An additional boost to the event rate would arise with a next generation instrument with improved capabilities. While $^{57}\mathrm{Co}$ and $^{44}\mathrm{Ti}$ abundances may not allow detection of emergence luminosities lower than $\sim 10^{35}$ ergs s^{-1}, a more sensitive instrument will certainly increase the range over which higher emergence luminosities can be observed. In particular, we find that if the threshold apparent magnitude of the instrument can be improved to $m_v \sim 30$ (possible threshold for NGST), the expected event rate is increased by a factor of 6-8.

In conclusion, we suggest that observing emergence of a black hole in Type II supernovae is potentially possible even with present capabilities. In view of the relatively low rate, high priority should be assigned if a likely candidate supernova (low energy, low $^{56}\mathrm{Co}$) is discovered. The event rate would significantly enhanced with future improved instruments, and also through dedicated nearby faint supernova searches with present capabilities. Such a search based on ground instruments is currently being initiated (M. Turrato 2000, private communication), and could also be included as part of other projects aimed at observing high redshift supernova. In view of the importance of achieving direct confirmation of the supernova – black hole connection, we believe such efforts should be encouraged.

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